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ANARCHY, UNCERTAINTY, AND THE EMERGENCE OF PROPERTY RIGHTS

KARL WÄRNERYD*

This paper investigates whether Lockean first claimer property rights should be expected to emerge in anarchy. Individuals behind a veil of uncertainty about their future wealth decide independently whether to commit to using force. Neither the contractarian hypothesis that a thicker veil of uncertainty supports more co-operation nor Demsetz's hypothesis that well-defined property rights emerge as the value of the externality from not having private property increases is unambiguously implied by the model.

1. INTRODUCTION

THE PROPERTY rights principle that the first individual to claim a previously ownerless resource is to be considered its owner, sometimes called the *homestead* principle, is a basis for many classical liberal ethical systems (notably that of Locke 1967) and is recognized in common law. The reasons for the appearance of the principle in the two different instances must be thought to be different, however. In natural law ethics, the concept typically derives from metaphysical and epistemological axioms concerning the nature of reality, human nature, etc, and is an imperative independently of whether any individual ever chooses to respect it. Common, or judge-made, law, on the other hand, is an evolutionary process of pragmatic human social problem solving. In this paper, I will be concerned with explanations of when and why we in the latter case (and similar situations of decentralized decision-making) would expect the homestead principle to emerge spontaneously.

Curiously few economists have devoted attention to state-of-nature theory, i.e., the study of situations where there are no institutional constraints on individuals' use of violence to get what they want. Some exceptions are Buchanan (1975), Bush (1972), Sugden (1986) and Umbeck (1981). The latter tests his theory of rights creation in anarchy using empirical data from the nineteenth-century gold rush in California. Although the model presented here differs radically from Umbeck's, I have retained the suggestive gold miner framework.

In evolutionary biology, the theoretical situation is different. Respect for first claimer "rights" when individuals are in potential conflict over a resource has been empirically observed, for instance am . ng baboons. The seminal

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game-theoretic analysis of this appearance of the homestead principle is due to Maynard Smith and Price (1973), in an article that is also the first example of the *evolutionary game theory* approach (see Maynard Smith (1982) or van Damme (1987) for comprehensive introductions). If an individual is genetically programmed to be either aggressive or passive, resource possessors meet randomly with non-possessors for interaction, and a given individual is as likely to be in possession of something as not, Maynard Smith and Price find conditions for non-violence to be viable equilibrium behavior.

One motivation for the present paper has been, in applying this kind of thinking to human societies, to investigate the results of allowing the probability of being in the possessor role to be something else than 1/2. However, to maintain tractability, I drop the assumption that behavior can be conditioned on possession.

That the model is discussed in terms of gold mining is not intended to reflect a limitation of the scope of conclusions to such scenarios only. From the Lockean construct a variety of comprehensive rights could possibly be derived (see, eg, Nozick 1974). Most notably the homestead principle seems to imply the individual's right to the product of his talents. Income redistribution schemes interfere with such a notion.

One question of interest in this context is whether the presence of a higher relative degree of uncertainty about one's own future position would, as argued by Brennan and Buchanan (1985, p 28 ff), make individuals more inclined to cooperative solutions, i.e., lead them to desire a stronger commitment to well-defined property rights. Since my aim is a positive theory, however, I replace the social-contract-theoretic approach of Brennan and Buchanan with a noncooperative game situation. Co-operative solution concepts ultimately depend on the possibility of enforcement. It is now generally accepted in game theory that enforcement mechanisms should be modeled explicitly if possible. In this sense, the present model may be said to deal with the micro-foundations of constitutional economics in the Buchanan sense.

Another prominent hypothesis about property rights is that of Demsetz (1967), who argues that communal property rights are viable only as long as the externality associated with them is not valuable enough. This may also be investigated within the framework of the model of the present paper.

The paper is organized as follows. Section 2 introduces a simple model of a non-cooperative binary choice situation, related to the biological model, but with a built-in asymmetry of possession. The variance of the distribution of wealth is interpreted as an operationalization of the contractarian idea of a veil of uncertainty or ignorance. It is also a measure of the inequality of the income distribution.

Section 3 discusses equilibria of the model. Uncertainty in the contractarian sense is crucial, but a set of cases can be identified where it works contrary to the contractarian hypothesis. This is due to the fact that increased uncertainty,

or income inequality, also means that, for some, the expected value of not respecting property is correspondingly greater.

In Section 4 I argue that the equilibrium is a stable fixpoint of an evolutionary process of imitation of successful decisions in the repeated game, analogous to the "evolutionary stability" discussed by Maynard Smith in biological models.

Finally, in Section 5, I discuss possible implications of the model for real world societies.

2. THE MODEL

2.1 *Players and Strategies*

There is a continuum of individuals on the interval $[0,1]$. All individuals have the same von Neumann-Morgenstern utility function $U(x)$, where x is gold consumption. Furthermore, $U'>0$ in the relevant interval.

At the beginning of the game period, each individual decides whether to make an investment in a mechanism of aggression, incurring a cost $c \geqslant 0$. This is the only decision to be made in the game. The set of pure strategies available to each individual is thus $S=\{I,N\}$, where I denotes a decision to make the investment and N a decision not to.

The investment is a commitment. It can be thought of as similar to a decision (perhaps made in a depressed frame of mind) to pay a professional "hit man" to kill you (or, in this case, someone else), despite whether you later change your mind, under certain objective circumstances at a future date. Or perhaps it is a time bomb that cannot be disarmed once activated. This assumption has the same function here that the notion of genetically programmed behavioral commitment has in the biological game mentioned earlier. However, it could be supported on a subgame perfectness argument if the choice of using or not using the aggression mechanism was explicitly allowed at a later point in the game. Since, as will be assumed, the individual will have nothing to lose from using his aggression option, once it is present and its cost therefore sunk, doing so is compatible with rationality.

2.2 *The Veil of Uncertainty*

Having made the investment decision, each individual is randomly allocated one *site*, which may or may not turn out to contain a unit of gold. The probability of finding a unit of gold at a particular site is α, with $\alpha \in [0,1]$. Therefore, when the allocation is complete, an expected share α of the population will be *possessors* of gold, and a share $1-\alpha$ *non-possessors*.

Now $\sigma := \alpha(1-\alpha)$ is the variance of the single sample distribution of sites containing a unit of gold. The variance σ is a measure of the uncertainty facing

agents about which role, possessor or non-possessor, they will occupy in the future game. It may be thought of as corresponding to the "veil" of uncertainty or ignorance behind which social contract theories such as those of Buchanan and Rawls require that individuals come to unanimous agreement. It is also a measure of the inequality of the *ex post* income distribution.

The thickness of this "veil" behind which decisions must be made will turn out to influence what is to be considered a good strategy choice. However, this will also depend on the expected value α. Because of its quadratic nature, each value of σ is associated with two values of α, one of which is "high" in the sense of being larger than 1/2, and the other one "low". This turns out to complicate the total effect.

2.3 *Interaction and Payoffs*

Individuals now meet randomly in pairs. In case a possessor is paired with a possessor, which is expected to occur in a share α^2 of all pairs, we shall assume both exit the encounter with their original allocations, regardless of aggression investments. This may be because you cannot carry more than one unit of gold, or because satiation occurs at one unit.[1]

The possible outcomes for each party in this pairing, viewed from the *ex ante* position, may be summarized as follows:

$$\Pi_{P,P} = \begin{matrix} \\ I \\ N \end{matrix} \begin{matrix} \begin{matrix} I & \quad N \end{matrix} \\ \begin{pmatrix} U(1-c) & U(1-c) \\ U(1) & U(1) \end{pmatrix} \end{matrix},$$

where the rows represent the arms situation of the individual to whom the payoffs accrue, and the columns that of his opponent.

Similarly, in case a non-possessor meets a non-possessor, which will be the case in a share $(1-\alpha)^2$ of all pairs, nothing happens. That is, we have that

$$\Pi_{\text{Non-P,Non-P}} = \begin{matrix} \\ I \\ N \end{matrix} \begin{matrix} \begin{matrix} I & \quad N \end{matrix} \\ \begin{pmatrix} U(-c) & U(-c) \\ U(0) & U(0) \end{pmatrix} \end{matrix}.$$

Finally, if a possessor meets a non-possessor, the non-possessor exits with the possessor's gold if the former has invested in the aggression mechanism while

[1] This is a crucial and perhaps controversial assumption. For instance, Hobbes's claim that the will to power is insatiable is a central feature of his argument for the necessity of a Sovereign. A referee notes that "history is full of instances of rich people fighting each other for each other's wealth". In defense of the assumption I can only offer that it allows us to get results based only on risk aversion assumptions about the utility function, whereas more detailed (and arbitrary) assumptions about its shape would be necessary otherwise.

the latter has not. In case both have made the investment, let there be a probability β, not necessarily equal to 0.5, that the possessor gets to keep his unit of gold. The outcomes for a possessor in such a pair are therefore

$$\Pi_{\text{P,Non-P}} = \begin{matrix} \\ I \\ N \end{matrix} \begin{matrix} \begin{matrix} I & \quad N \end{matrix} \\ \begin{pmatrix} \beta U(1-c)+(1-\beta)U(-c) & U(1-c) \\ U(0) & U(1) \end{pmatrix} \end{matrix},$$

while those of the non-possessor are

$$\Pi_{\text{Non-P,P}} = \begin{matrix} \\ I \\ N \end{matrix} \begin{matrix} \begin{matrix} I & \quad N \end{matrix} \\ \begin{pmatrix} (1-\beta)U(1-c)+\beta U(-c) & U(1-c) \\ U(0) & U(0) \end{pmatrix} \end{matrix}.$$

From the viewpoint of the *ex ante* position, i.e., when the investment decisions are to be made, an individual will be the possessor in such a pair with probability $\alpha(1-\alpha)$, and the non-possessor with the same probability.

The game situation may now be given a description in terms of the payoff structure for a single individual, conditional on the choices of all others.

- The individual has made the investment.

  —All others have also made the investment. The expected payoff for each individual is then $\alpha^2U(1-c)+(1-\alpha)^2U(-c)+\alpha(1-\alpha)(\beta U(1-c)+(1-\beta)U(-c))+\alpha(1-\alpha)((1-\beta)U(1-c)+\beta U(-c))=\alpha U(1-c)+(1-\alpha)U(-c)$. Note that the (possibly) conditional probabilities of winning the fight cancel, since you are equally likely to be in either role.

  —No one else has made the investment. There are three possible cases in which the individual exits with a unit of gold: When he is a possessor and meets another possessor (with probability α^2), when he is possessor and meets a non-possessor (with probability $\alpha(1-\alpha)$), and when he is non-possessor and is paired with a possessor (with probability $\alpha(1-\alpha)$). The expected payoff for the individual is then $(2\alpha-\alpha^2)U(1-c)+(1-\alpha)^2U(-c)$.

- The individual has not made the investment.

  —All others have made the investment. The expected payoff for the individual is then $\alpha^2U(1)+(1-\alpha^2)U(0)$.

  —No one else has made the investment either. The expected payoff for each individual is then $\alpha U(1)+(1-\alpha)U(0)$.

Equivalently, the *ex ante* payoff structure may be summarized as follows:

$$\Pi = \alpha^2\Pi_{\text{P,P}} + (1-\alpha)^2\Pi_{\text{Non-P,Non-P}} + \alpha(1-\alpha)\Pi_{\text{P,Non-P}} + \alpha(1-\alpha)\Pi_{\text{Non-P,P}}.$$

The matrix columns now represent the choice of the opponent one has met:

$$\Pi = \begin{array}{c} \\ I \\ N \end{array}\begin{pmatrix} I & N \\ \alpha U(1-c)+(1-\alpha)U(-c) & (2\alpha-\alpha^2)U(1-c)+(1-\alpha)^2U(-c) \\ \alpha^2U(1)+(1-\alpha^2)U(0) & \alpha U(1)+(1-\alpha)U(0) \end{pmatrix}.$$

The elements of this matrix will be referred to as π_{ij}, with i, j the names of strategies in S.

3. EQUILIBRIUM

3.1 A Classification of Social States

Bush (1976) notes that there is a tendency to rigidly define "anarchy" either as dangerous chaos (the more common view) or as peaceful voluntary co-operation, depending on what one believes about human nature. However, the Hobbesian jungle, or "war of each against all", and Proudhonian orderly anarchy are really located at opposite ends of a spectrum. The world we live in, in which a subset of individuals monopolize the use of violence for protection and redistribution of wealth, lies in between these two extremes.

Denote by n_I the Lebesgue measure of the subset of individuals that have made the aggression investment, and by $n_N = 1 - n_I$ the corresponding measure for those who have not. Various values of n_I may now be given interpretations in terms of implied property rights systems.

The Hobbesian jungle. $n_I = 1$. All individuals invest in aggression. There is no respect for the rights of anyone.

"Leviathan". $n_I \in (0,1)$. Some individuals invest in aggression. Some individuals (a share $n_N\alpha(1-\alpha)$) will *ex post* turn out to have "respected" homestead rights as non-possessors meeting unarmed possessors. There is some transfer of resources from unarmed possessors to armed non-possessors. There is some enforcement by possessors of their claims. There is of course no useful distinction here between *private* and *organized* enforcement of rights, such as in Hobbes's original discussion of Leviathan; the point is that there is resource loss because of the need for defense. For these purposes, n_I may be seen as a measure of the "size of government", since it measures the share of individuals who are willing to pay for defense of their rights of possession or to have resources transferred to them should they be unlucky allocation-wise.

Anarchic co-operation. $n_I = 0$. No one invests in aggression. There can be said to be voluntary respect for homestead rights. There is no social resource loss due to a need for defense.

3.2 *Equilibria*

I will consider only equilibria in pure strategies. There can, of course, depending on parameter values, be at most two different symmetric equilibria in pure strategies simultaneously in existence in the game.

The "Hobbesian jungle" (HJ) equilibrium exists when making the aggression investment is a best response to everyone else making the investment, i.e., when

$$\pi_{II} \geq \pi_{NI}, \tag{1}$$

which is equivalent to

$$\alpha U(1-c) + (1-\alpha)U(-c) \geq \alpha^2 U(1) + (1-\alpha^2)U(0).$$

The "anarchic cooperation" (AC) equilibrium exists when

$$\pi_{NN} \geq \pi_{IN}, \tag{2}$$

i.e., when

$$\alpha U(1) + (1-\alpha)U(0) \geq (2\alpha - \alpha^2)U(1-c) + (1-\alpha)^2 U(-c).$$

Proposition 1: *The situation with $n_I = 0$ (anarchic cooperation) Pareto-dominates $n_I = 1$ (the Hobbesian jungle).*

Proof: Forming the difference between the expected individual payoffs in the two situations, we find that

$$\pi_{NN} - \pi_{II} = \alpha(U(1) - U(1-c)) + (1-\alpha)(U(0) - U(-c)) > 0, \quad \text{for all } \alpha \in [0,1],$$

by monotonicity. □

This means that the "thickness" of the veil of uncertainty (i.e., the value of σ) lacks bearing on the relative equilibrium status of the AC and HJ situations in the hypothetical co-operative game suggested by Brennan and Buchanan. That is, if there was some enforcement mechanism to ensure that agreements were followed, and unanimous approval of investment decisions was required, only the proposal that none make the investment could be a co-operative solution.

There are now four different conceivable cases: Both, none, or only one of the equilibria may exist.

The two symmetric equilibria exist simultaneously when conditions (1) and (2) both hold. This implies, however, that the individuals are risk lovers or risk neutral.

Proposition 2: *If individuals are risk averse, i.e., have strictly concave expected utility functions, then if any symmetric equilibrium in pure strategies exists, it is unique.*

Proof: To prove this, assume that both the HJ and AC equilibria exist simultaneously. This means that $\pi_{II} \geqslant \pi_{NI}$ and $\pi_{NN} \geqslant \pi_{IN}$. This implies, by summing the inequalities and rearranging, that

$$\pi_{II} - \pi_{NI} + \pi_{NN} - \pi_{IN} \geqslant 0$$

or

$$\sigma(U(1) - U(0) + U(-c) - U(1-c)) \geqslant 0.$$

Since $\sigma \geqslant 0$, this would imply that $U(1) - U(0) \geqslant U(1-c) - U(1-c)$. But then U cannot be a strictly concave function, since in general if $f: R \to R$ is a strictly concave function, then, for any x, x' such that $x' > x$, and for any $\delta > 0$, we have that $f(x' + \delta) - f(x') < f(x + \delta) - f(x)$. Therefore any symmetric equilibrium in pure strategies is unique. □

When only one of (1) and (2) holds, however, one strategy strictly dominates the other, regardless of risk attitudes. In case (1) holds and (2) does not, the game has the familiar "Prisoners' Dilemma" (PD) structure, where the dominant strategy leads to an inefficient equilibrium.

In particular, it is enlightening to consider for a moment the special case that arises when individuals are risk neutral, i.e., have linear expected utility functions. We then have that (1) reduces to

$$c \leqslant \sigma.$$

Conversely, the AC equilibrium exists when

$$c \geqslant \sigma.$$

When the latter holds strictly, what we have is that happy (but seldom discussed—unless one counts extremely naïve readings of Adam Smith) thing, a game situation where adopting the efficient strategy is a dominant way of behaving. We might christen it the "Inverse Prisoners' Dilemma" (or DP).[2]

When we have that $c = \sigma$, all possible outcomes are equal and any population proportions constitute an equilibrium.

Now assume a uniform distribution over the parameter space, and let $c < 1$. For a given value of α, the set of parameter values for which "anarchic

[2] It is sometimes called a *convergence game*.

co-operation" is an equilibrium is $\{c \in (0,1): c \geq \alpha(1-\alpha)\}$. The measure of this set is simply $1-\sigma$. When uncertainty is highest, i.e., when σ is at its maximum at 0.25, the "anarchic co-operation" set is smallest. In other words, the lesser is uncertainty, and the greater the cost of using violence, the larger is the scope for spontaneous cooperation.

The intuition for this result is very straightforward. Having made the investment will be useful only in possessor versus non-possessor conflicts. The probability of being one party in such a pairing is 2σ. The larger σ, and therefore this probability, and the smaller c is, the greater is the likelihood of everyone deciding that the investment is a good idea.

The uncertainty σ is, of course, at a maximum when the states of being possessor and non-possessor are equally likely. When α is small, a given player is most likely to be going to be "poor", and most of the other players are also going to be poor, so mixed conflicts, where something can be gained, will be rare. Similarly, when α is large, an individual will most likely be "rich", and this goes for his potential opponents as well, so that the investment in aggression will be unlikely to seem a worthwhile project.

Returning to the more realistic case of risk aversion, when neither condition (1) nor (2) holds, there is no symmetric equilibrium. However, there may be an asymmetric, or "Leviathan" equilibrium, that is, population proportions (n_I^*, n_N^*) such that expected payoffs are equalized over the strategies,[3] so that

$$n_I^* \pi_{II} + n_N^* \pi_{IN} = n_I^* \pi_{NI} + n_N^* \pi_{NN}. \tag{3}$$

We may now prove the following general existence result.

Proposition 3: *A symmetric or asymmetric equilibrium for the game exists.*

Proof: We already know that a symmetric equilibrium may exist. Equation (3) together with the condition that the equilibrium population proportions sum to 1 may be written as the equation system

$$\begin{pmatrix} \pi_{II} - \pi_{NI} & \pi_{IN} - \pi_{NN} \\ 1 & 1 \end{pmatrix} \begin{pmatrix} n_I^* \\ n_N^* \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

which has the solution

$$n_I^* = \frac{\pi_{NN} - \pi_{IN}}{(\pi_{II} - \pi_{NI}) + (\pi_{NN} - \pi_{IN})}. \tag{4}$$

[3] It should be noted that this definition of an equilibrium really has three different interpretations. The one used here is that of an asymmetric equilibrium in pure strategies. It could also be a symmetric equilibrium in mixed strategies, with (n_I^*, n_N^*) the probabilities assigned by all players to strategies I and N, respectively. Finally, it could define a truly polymorphic situation where individuals use different mixed strategies, but where the aggregate probabilities are (n_I^*, n_N^*).

If neither symmetric equilibrium exists, it can easily be checked that $n_I^* \in (0,1)$, which guarantees the existence of at least one equilibrium. □

Correspondingly, we have that

$$n_N^* = 1 - n_I^* = \frac{\pi_{II} - \pi_{NI}}{(\pi_{II} - \pi_{NI}) + (\pi_{NN} - \pi_{IN})}.$$

Proposition 4: *The asymmetric equilibrium is inefficient for* $\alpha \in (0,1)$.

Proof: This can be proved by noting that the expected payoff to each individual is equal to $n_I^* \pi_{NI} + n_N^* \pi_{NN}$. We have that $\pi_{NN} \geq \pi_{NI}$ since

$$\pi_{NN} - \pi_{NI} = \sigma(U(1) - U(0)) \geq 0$$

by monotonicity. Since the expected payoff at the asymmetric equilibrium is a convex combination of π_{NN} and π_{NI}, it is equal to or lower than π_{NN}. Each individual would be as well off if all chose strategy N for $\alpha \in \{0,1\}$, and better off for $\alpha \in (0,1)$. □

If the cases where one of (1) and (2) holds are included, we get the domination equilibria as limit cases of the asymmetric equilibrium, so that $n_I^*, n_N^* \in [0,1]$. Therefore, only the behavior of the asymmetric equilibrium population proportions needs to be studied.

Unsurprisingly, the larger the cost of the investment as a share of what can be gained, the smaller is the equilibrium arsenal.

Proposition 5:

$$\frac{\partial n_I^*}{\partial c} < 0.$$

Proof: This is found by differentiating (4). Let $M = \pi_{NN} - \pi_{IN}$ and $D = \pi_{II} - \pi_{NI} + \pi_{NN} - \pi_{IN}$. Then

$$\frac{\partial n_I^*}{\partial c} = \frac{M_c D - D_c M}{D^2},$$

where the subscripts denote derivatives. We have that $M, D < 0$ by the non-existence of symmetric equilibria, $M_c = (2\alpha - \alpha^2)U'(1-c) + (1-\alpha)^2 U'(-c) > 0$, and $D_c = \sigma(U'(1-c) - U'(-c)) < 0$ by strict concavity, which makes the expression negative. □

The role of uncertainty in this general context is partly indeterminate, i.e., it will depend on the specific shape of the utility function. We might want to ask, for instance, what the effect of a small change in σ due to a continuous adjustment of α would be on n_I^*. That is, by excluding sudden jumps in α, we could consider it locally a function of σ and differentiate.

Proposition 6:

$$\left.\frac{\partial n_I^*}{\partial \sigma}\right|_{\alpha<1/2} \gtrless 0.$$

Proof: We have that

$$\frac{\partial n_I^*}{\partial \sigma} = \frac{(M_\alpha - D_\alpha)(\pi_{NN} - \pi_{IN}) + M_\alpha(\pi_{II} - \pi_{NI})}{D^2} \frac{\partial \alpha}{\partial \sigma}.$$

For $\alpha < 1/2$, we have that $M_\alpha = U(1) - U(0) - 2(1-\alpha)(U(1-c) - U(-c)) < 0$, $M_\alpha - D_\alpha = 2\alpha(U(1) - U(0)) - (U(1-c) - U(-c)) < 0$, and $\partial\alpha/\partial\sigma \gtrless 0$. □

That is, for a situation with poor prospects, an increase in uncertainty (due to an increase in the expected value α) would make the equilibrium size of "Leviathan" larger. For $\alpha \gtrless 1/2$, nothing can be said without further assumptions about the functional form of U.

This also says something about the theory of property rights in Demsetz (1967). Demsetz argues that private property rights (which would correspond to non-aggression in the present model) emerge as the value of resources extracted (here, α) increases. Clearly, we have identified an interval where this is not true.

4. EVOLUTIONARY STABILITY

Now imagine this interaction structure reoccurs over many periods. The agents (or possibly new generations) are in each period confronted with a new field of sites, all having the same frequency of gold sites, and an identical investment decision to be made. In keeping with the property-rights analysis in evolutionary biology one might now want to know the likelihood of the static equilibria occurring as steady states in such a dynamical system.

Explanations based on genetic selection, i.e., by differential reproductive capacity in agents, have a dubious status in the social sciences. Assuming, however, that agents are boundedly rational and update their strategy choices from period to period based on observed results, we get a process of *cultural evolution* similar to the genetic evolution primarily studied by evolutionary biologists.

When the expected values of investing and not investing are equal, no agent who has made one type of decision could observe agents who have made the other do better on average. A reasonable updating process therefore has the asymmetric equilibrium defined above as a fixpoint. We further want it to be stable in the sense that if it is upset, for instance by an influx of new players having different proportions of aggressors and non-aggressors, the population would with the passing of time return to the equilibrium.

Note that the asymmetric equilibrium in pure strategies is mathematically identical with a symmetric equilibrium in mixed strategies for a 2×2 symmetric bimatrix game. Because of this, we can apply Maynard Smith's stability concept directly. It says that a strategy is considered stable if in a population where everyone except a very small minority of mutants play it, its expected payoff is greater than that of the mutant strategy. That is, if Γ is an arbitrary symmetric two-player game, where each player has a pure strategy set $S = \{s_1, s_2, \ldots, s_m\}$ and von Neumann-Morgenstern payoff function $P: S \times S \rightarrow R$, then a strategy $s^* \in S$ is stable if for every mutant $s \in S$ played by a small proportion ϵ of the population, we have that

$$(1-\epsilon)P(s^*,s^*) + \epsilon P(s^*,s) > (1-\epsilon)P(s,s^*) + \epsilon P(s,s).$$

It is easily seen that this condition is equivalent to the one in the following original definition of evolutionary stability.

Definition 1 (Evolutionary Stability): *A strategy $s^* \in S$ is said to be an* evolutionary stable strategy (ESS) *of Γ if, for all $s \in S$,*

$$P(s^*,s^*) \geqslant P(s,s^*),$$

and if $P(s^*,s^*) = P(s,s^*)$ then

$$P(s^*,s) > P(s,s).$$

Clearly, this is a rather general and reasonable requirement for stability in any strategy dynamics. (Even so, an ESS fails to exist in many games.) While the concept is thus not necessarily linked to models of genetic reproduction, mixed ESSs can be shown to correspond to asymptotically stable population proportions of the so-called replicator dynamics, which models asexual genetic reproduction. (See Taylor and Jonker (1978).)

Now consider the asymmetric equilibrium n_I^* of our present model as a symmetric mixed strategy equilibrium.

Proposition 7: *The mixed strategy (n_I^*, n_N^*) is an ESS.*

Proof: As a mixed strategy, which equalizes the expected payoffs of the two pure strategies, (n_I^*, n_N^*) has a continuum of alternative best replies. Therefore we have to check the second part of the ESS criterion. Let $q_I \in [0,1]$ be the probability associated with making the aggression investment of an arbitrary alternative best reply strategy. Further define the vectors $n = (n_I^*, 1 - n_I^*)$ and $q = (q_I, 1 - q_I)$. Letting x^T denote the transpose of a vector x, the expected payoff of the equilibrium strategy against the arbitrary mutant is then $n\Pi q^T$, and that of the mutant against itself $q\Pi q^T$. Forming the difference, we find that

$$n\Pi q^T - q\Pi q^T = -\frac{(\pi_{NN} - \pi_{IN} + q_I(-\pi_{II} + \pi_{IN} + \pi_{NI} - \pi_{NN}))^2}{(\pi_{II} - \pi_{NI}) + (\pi_{NN} - \pi_{IN})},$$

which, under the assumptions guaranteeing existence of the equilibrium, is positive except when $q_I = n_I^*$. So the equilibrium is stable in the sense of ESS. □

5. CONCLUDING REMARKS

To reiterate the starting-point of this study, an approach more common than the one in this paper to discussions of the origin of property rights takes as given the ability of a group of individuals to unanimously agree to abide by rules enforced by a third-party outsider. In this contractarian framework, as represented by, e.g., the work of Buchanan (1975) and Brennan and Buchanan (1985), it seems reasonable that an increase in the degree of uncertainty about future individual positions would indeed lead individuals to desire more well-defined property rights. But nothing corresponding to the hypothetical social contract with an external enforcer exists in the real world. We must therefore check that the result is not an artifact of the cooperative game model. The purpose of this paper has been to investigate whether a similar result holds in a noncooperative model that has a veil of uncertainty defined in a way closely related to that in the cooperative framework. We were able to identify circumstances such that the hypothesis does not hold.

It might be objected that there is nothing closely resembling enforcement of property rights in this model. After all, the situation identified as one with perfectly defined property rights is the one where no aggression mechanism is present at all. It is important to stress that such a notion of property rights is slightly different from the one found in contractarian discussions. In the latter, property rights are necessarily the result of the central enforcement of law. One might argue from a natural rights perspective that in such a situation there is really no private property at all, merely possessions granted by the enforcement agency. This case corresponds fairly well to the asymmetric equilibrium of the present model. Here some individuals choose to, in effect, respect the property rights of others by not investing in aggression capabilities. This is generated by the threat of punishment from aggressors should they lose in a conflict situation. A subgroup of armed individuals therefore come to play the role of something that would seem to correspond to the external enforcer of the contractarian story.

Most of actual economic and social life does not have the character of "gold-mining" in the sense discussed above. For instance, there is production. Although the model might at first glance seem somewhat removed from contemporary circumstances in most places, it could perhaps nonetheless say something about property rights and redistribution in actual societies. To begin with, the model's variables relate to observable measures. Note, for instance, that the variance σ may also be seen as an "inequality" measure for the income distribution, directly related to the entropy measure discussed by Theil (1967). (The use of the

information-theoretical term "entropy", which is equivalent to "uncertainty", by Theil should be especially intriguing to contractarians concerned with decisions made behind "veils".)

Although it is not immediately obvious how one would best measure the degree of respect for individual property rights in talent and its product (although transfer payments as a share of GNP might be one example), the above discussion would lead us to expect poor societies with a large degree of pre-tax income inequality also to have a lesser degree of such respect, if the costs of using violence are equal across societies.

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